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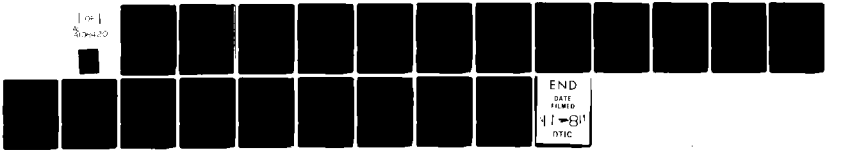

LEVEL II

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ANALYSIS OF DATA FOR THE DEVELOPMENT OF DENSITY AND COMPOSITION MODELS OF THE UPPER ATMOSPHERE

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Analysis of Data for Development of Density/Composition Models of the Upper Atmosphere

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Work was directed toward the ultimate goal of developing an improved model of the temperature, density, and composition of that region of the earth's neutral atmosphere above the turbopause. A wealth of data has become available, mainly in the form of total density and composition from satellite-borne mass-spectrometers, in recent years. Most of the work performed under the contract consisted of the analysis of data from the ESRO 4 mass spectrometer with a view towards improvement of the model of the geomagnetic variation in the thermosphere and exosphere.

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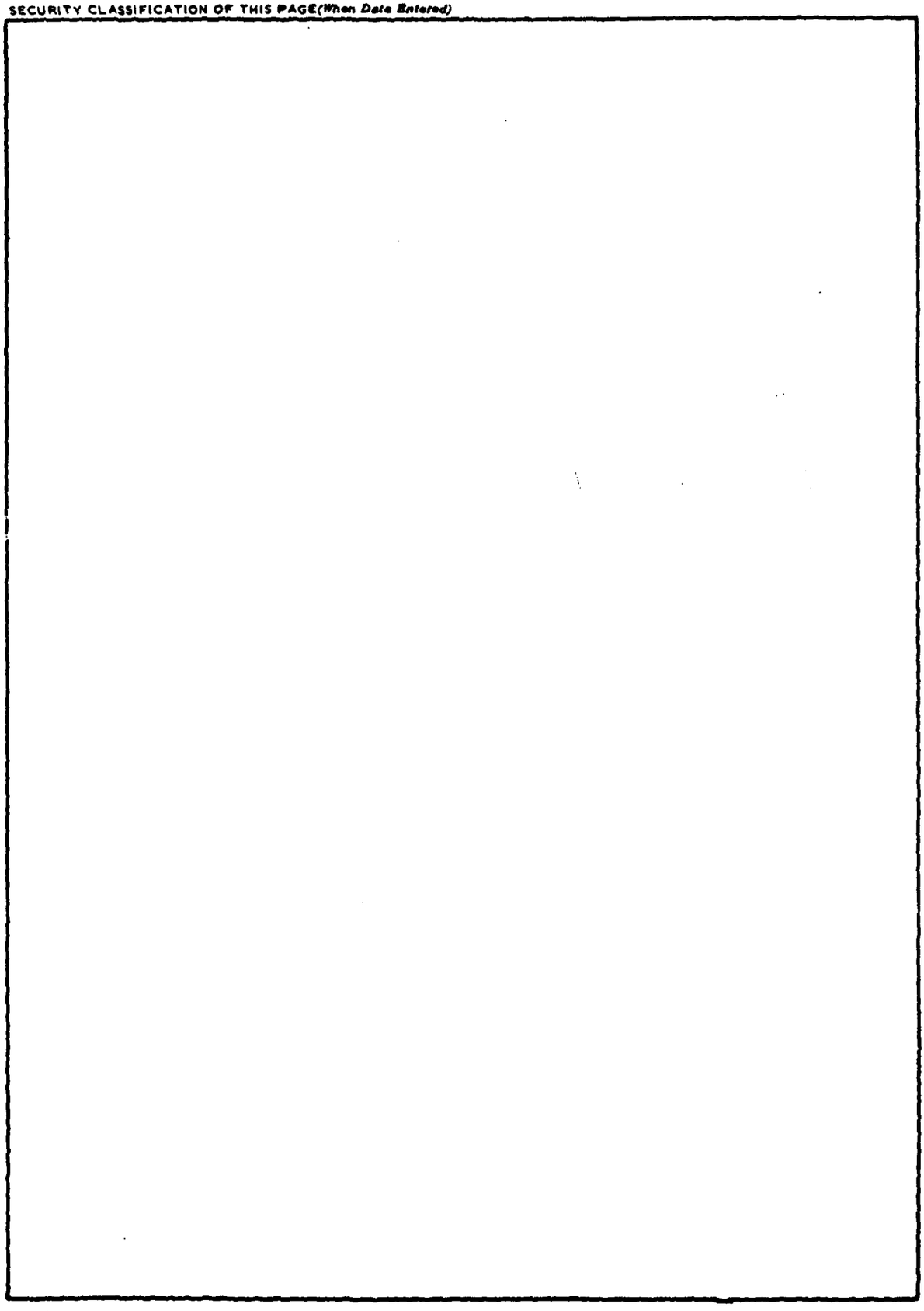

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I. Introduction

Work under this contract was directed toward the ultimate goal of developing an improved model of the temperature, density, and composition of that region of the earth's neutral atmosphere above the turbopause (thermosphere and exosphere). For many years, the only data pertaining to this important region consisted of total densities obtained from the drag on artificial satellites. More recently,a wealth of more detailed data, mainly in the form of total density and composition from satellite-borne mass-spectrometers, has become available. Most of the work performed under the contract consisted of the analysis of data from the ESRO 4 mass spectrometer with a view towards improvement of the model of the geomagnetic variation in the thermosphere and exosphere. This is summarized in what follows.

II. Geomagnetic Variation: Overview

In earlier work, we had derived a longitudinally averaged model of the geomagnetic variation in the thermosphere (Jacchia et al [1], [2]) based on analysis of mass spectrometer data from the ESRO 4 satellite. This model was incorporated, with a revision to the form of the temperature profiles during times of geomagnetic disturbance, in the 1977 Jacchia model atmosphere (Jacchia [3]). Shortly thereafter, the results of the revision to the form of the temperature profiles, which had required numerical integration to be implemented, were put into analytic form.

Work under this contract was directed mainly toward the improvement of this earlier model. The earlier work had utilized data from only a relatively few periods of prolonged disturbance. The data base was expanded to include all of the ESRO 4 measurements pertaining to disturbed conditions and statistical methods were applied to this data base. In this, we were helped considerably by the availability of a model fitted specifically to the ESRO 4 quiet-time data (von Zahn, et al [4]) for use as a reference. The objective of the work was not only to refine the details of the model in its earlier form but to determine what details of the longitudinal and/or local time structure of the variation could be established and incorporated into a working model. The longitudinal structure is of interest not only from a

practical point of view but because of what it can reveal about the sources of energy and the dynamics of the disturbed thermosphere.

Our earlier model of the geomagnetic variation is composed of three separate effects: a thermal increase centered in high geomagnetic latitudes; a variation in the height of the turbopause that causes lighter constituents to vary in the opposite sense from heavier constituents; and an "equatorial wave", centered in low latitudes, in which all constituents increase in the same proportion. Some qualitative results of the new analysis were:

1. The amplitude of the equatorial wave in the earlier model is essentially correct: on the average, there are no significant residuals between the observed and computed values at the equator for even the highest levels of geomagnetic activity. The equatorial wave does not, however, diminish with increasing latitude as sharply as had been previously assumed; it is significant almost to the poles.

2. There is no appreciable variation in the longitudinally averaged latitude profiles of the increase in exospheric temperature with either season or hemisphere discernable in the ESRO 4 data (at a height of 280 km).

3. The increase in exospheric temperature in the vicinity of the magnetic poles as given by the earlier model is essentially correct. There is an indication that the predicted value may be too large by as much as 20% for very large disturbances. The paucity of data corresponding to highly disturbed conditions does not permit a definitive answer to this question, however.

4. The latitudinal gradient of the increase in exospheric temperature is, on the average, lower than that given by the earlier model. In addition, the profiles are appreciably flattened in high geomagnetic latitudes. The polar maximum is relatively sharp for values of the Kp geomagnetic index up to about 4. For $6 \leq Kp < 7$ - the highest range for which we have a significant amount of data from ESRO 4 - there is only a slight poleward slope above about 40 degrees latitude, however.

5. The magnitude of the increase in the height of the turbopause is approximately 30% too large. This has quite a large effect on the predicted variations of atomic oxygen and the total density. The behavior of atomic oxygen under disturbed conditions represents a rather delicate balance in middle and high latitudes between the increase associated with the increase in exospheric temperature and the decrease that we have linked to an increase in the height of the turbopause. Thus, any change in the assumed increase in the height of the turbopause will have a disproportionate effect on the derived atomic oxygen density.

And atomic oxygen dominates the total density except at very high temperatures throughout most of the thermosphere.

6. The increase in exospheric temperature (as derived from the molecular nitrogen densities) and the variations of all of the constituents show a strong dependence on local magnetic time. This is to be expected since the principal energy sources in the disturbed thermosphere, particle precipitation and Joule heating, act at a distance from the magnetic poles and vary greatly with local magnetic time. We were able to identify the main features in the global variations of all of the atmospheric constituents measured by ESRO 4 and to associate most of these with the corresponding features in other constituents and with expected energy sources. A more detailed summary of these results will be given further on in this report.

III. Longitudinally Averaged Model

One result of the new analysis was a revision of the earlier longitudinally averaged model to eliminate some of the discrepancies mentioned above. Since this revision has not yet been published, it is briefly summarized here.

The earlier model is represented by the following equations (numbered as they are in the 1977 Jacchia model):

$$\Delta_G \log n_i = \Delta_T \log n_i + \Delta_H \log n_i + \Delta_e \log n_i \qquad (28)$$

$$\Delta_G T_\infty = A \sin^m \phi_I \qquad (31a)$$

where

$$A = 57.5K_p' \left[1 + 0.027 \exp\left(0.4K_p'\right)\right] \qquad (31b)$$

and Kp' is the appropriately "lagged" value (equation 30, 1977 Jacchia model) of the Kp geomagnetic index.

$$\Delta_H \log n_i = \alpha_i \Delta z_H \qquad (34)$$

where

$$\Delta z_H = 5.0 \times 10^3 \sinh^{-1}\left(0.010\, \Delta_G\, T_\infty\right), \qquad (33)$$

and

$$\Delta_e \log n_i = 5.2 \times 10^{-4}\, A \cos^n \phi_I. \qquad (35)$$

The values of the exponents m and n were originally both given as 4.0 and the values of α for use in equation 34 as (mks units):

$$\begin{aligned} \alpha(Ar) &= 3.07 \times 10^{-5} \\ \alpha(O_2) &= 1.03 \times 10^{-5} \\ \alpha(N_2) &= 0. \\ \alpha(O) &= -4.85 \times 10^{-5} \\ \alpha(He) &= -6.30 \times 10^{-5} \end{aligned}$$

The thermal increase includes the effect of a disturbance to the temperature profiles (equation 32) that is included in an analytic representation of the thermal increase that is currently in use in the model. That part of the model is unchanged in the revised version, however, and the equation need not be repeated here.

The revisions to the model are as follows:

1. The values of the exponents m and n are changed to 3.0 and 2.0, respectively. Note that these values are appropriate to the case of high temporal resolution as when comparisons are made with mass spectrometer or similar data. In the case where the observed data represent a smoothing over an appreciable part of the day, the geographic latitude should be taken as the argument in the equations and the appropriate values of m and n are 2.8 and 1.8, respectively. The corresponding value of the multiplying constant (57.5) in equation 31b is 54.2.

2. Equation 33 for the increase in the height of the turbopause should be replaced by

$$\Delta z_H = 22.0\ \Delta_G T_\infty .$$

The main effect of this change is to reduce the increase in the height of the turbopause to about 65% of the original value. This change was dictated by all of the constituents measured by ESRO 4 and not just by atomic oxygen (and the total density). The effect on atomic oxygen is, in fact, offset somewhat by revision 3 (see below).

3. The value of $\alpha(0)$ is changed from -4.85×10^{-5} to -5.75×10^{-5}.

The main effect of this revision at low and moderate heights in the thermosphere is to greatly increase the response of atomic oxygen and the total density to geomagnetic disturbance in middle latitudes. This has important consequences as far as use of the model to predict variations in density is concerned. In the earlier model, the increase in density associated with geomagnetic disturbance went almost to zero at low heights in middle latitudes. The response at low heights is nearly independent of latitude in the revised model and is in much better agreement with density results from other sources. As a test, a comparison was made between the model densities and those obtained from the drag on the Explorer 32 satellite (at an effective height $\simeq$300 km). The revised model gave much better agreement with the observed values than the earlier model did.

The revised model also predicts a greater increase in total density in middle latitude, and, to some extent, in high latitudes as well, than the original model did at greater heights. In this connection, it must be pointed out that both the original and the revised versions of the model were derived from mass-spectrometer data taken at 280 km and that the density variations predicted above that height represent an extrapolation. No really comprehensive test of either the original or revised versions of the model with regard to the latitudinal form and polar amplitude of the

predicted variations, including those of the total density, has been made at greater heights. This is a matter of some concern, especially with regard to the total density and the large amplitudes of the increases predicted by the model.

IV. Local-time Dependent Model

Development of empirical models of the thermosphere and exosphere is made difficult by the limited spatial and temporal coverage of the available observational data. This is especially true in the case of the geomagnetic variation, which is both spatially and temporally complex and of a transitory nature. The situation is aggravated by the fact that the available indices, though positive indicators of disturbance, are otherwise rather poorly correlated with the observed atmospheric phenomena.

Thus, we feel that our revised model of the geomagnetic variation represents a very significant contribution. A more detailed picture, showing the longitudinal as well as the latitudinal aspects of the variation, is essential to an understanding of the energy sources and dynamics of the disturbed thermosphere and of the interaction of the neutral atmosphere with other regions, however. Such a picture would, of course, have important practical value as well.

We made significant progress towards the developement of a more detailed model in our statistical analysis of the ESRO 4 data. Some qualitative results of that analysis for the temperature increase (deduced from the N_2 densities) and for Ar and He (both of which are important as indicators because they represent the extremes in atomic weight) are as follows:

1. There are two maxima in the temperature response in high geomagnetic latitudes. These maxima occur near the poleward limit of the auroral belts, at about 9 and 0 hours of local magnetic time (LMT). The maximum near 9 hours LMT is the more intense of the two. The positions of both maxima shift toward lower latitudes in the auroral belts as the level of disturbance increases, causing a considerable broadening in the form of the temperature profiles in high latitudes. The amount of this shift is 5-10 degrees in going from disturbances for Kp in the range 3-4 to those in the range 5-6. The LMT of the two maxima appears to remain constant. Both maxima would appear to be associated with heating due to particle precipitation.

2. There is clear evidence of the effect of Joule heating due to the auroral electrojets at somewhat lower latitudes within the morning and evening auroral belts. This takes the form of broad enhancements rather than any strong maxima, however. The effect is strongest on the morning side, in the

hours between midnight and dawn, where there is a slight indication of a secondary maximum just after midnight. We associate these features primarily with the westward electrojet system. The westward electrojet is the more intense of the two auroral electrojets and has two peaks, one in the evening sector and the other in the morning sector.

3. There is additional enhancement of the N_2 density in middle latitudes. This enhancement is absent in the hours between dawn and noon, but is appreciable throughout the nighttime hours and in the afternoon, with a fairly strong secondary maximum at 45° latitude in the late afternoon. This feature is associated with soft particle precipitation.

4. The Ar distribution is very similar to the N_2 distribution in both high and middle latitudes. The same maxima are observed at essentially identical locations in high latitudes. In middle latitudes, the enhancement throughout the nighttime hours and the secondary maximum in the late afternoon are both observed.

5. The He distribution shows two minima in high latitudes in the same locations as the two maxima in the N_2 distribution. There is also a minimum in the late afternoon corresponding to the secondary maximum in the N_2 distribution.

The features relating to the temperature increase are illustrated in the Figure which shows, as a function of geomagnetic latitude and local time, isotherms of the mean normalized temperature increase derived from data where the corresponding values of the Kp geomagnetic index were in the range 3-4. The complexity of the variation on a global basis is quite apparent from this figure and we have not yet devised a scheme that would adequately represent it analytically. The results of our analyses of the other constituents indicate, however, that, given such a scheme, a complete time-dependent model of the geomagnetic variation could be constructed with little difficulty.

V. Future Work

The analytic development of the local-time dependent model must, of course, be completed. Apart from this, there is an urgent need to extend the type of analysis we performed on the ESRO 4 data to data for both lesser and greater heights. This is important, not only in regard to those aspects of the longitudinally averaged model that have been mentioned, but is particularly important in regard to the more detailed model because of the possible effects of dynamics in the disturbed thermosphere. The obvious source for such data is, of course, the Atmosphere Explorer program,

particularly the results from the OSS mass-spectrometer experiment. We have initiated action to acquire these data, which are now available in large volume, from the National Space Science Data Center. Also, there is one important aspect of the geomagnetic variation that has so far received only cursory attention. That aspect is the time lag between a geomagnetic disturbance and the corresponding disturbance in the atmosphere. The time lag is important in the analysis of data and the utilization of models and, what is equally important, provides considerable insight with regard to the underlying physical processes. We have recently developed a method to determine the lag which we are applying to the ESRO 4 mass-spectrometer data and which we soon hope to apply to the Atmosphere Explorer data.

VI. Publications

Two papers were published as a result of partial sponsorship of the contract. These were:

1. J. W. Slowey

Models of the geomagnetic effect in the earth's thermosphere. Adv. Space Res., Vol. 1, pp. 213-219, 1981.

2. L. G. Jacchia

Empirical models of the thermosphere and requirements for improvements. Adv. Space Res., Vol. 1, pp. 81-86, 1981.

One scientific report was published under the contract. This was:

1. J. W. Slowey

Global Frequency Distribution of Exospheric Temperature. AFGL-TR-79-0143, Scientific Report No. 1, Smithsonian Institution, Astrophysical Observatory, 1979.

VII. References

1. L.G. Jacchia, J.W. Slowey, and U. von Zahn, J. Geophys. Res. 81, 36 (1976).

2. L.G. Jacchia, J.W. Slowey, and U. von Zahn, J. Geophys. Res. 82, 684 (1977).

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4. U. von Zahn, W.Kohnlein, K.H. Fricke, U. Laux, H. Trinks, and H. Volland Geophys. Res. Lett. 4, 33 (1977).

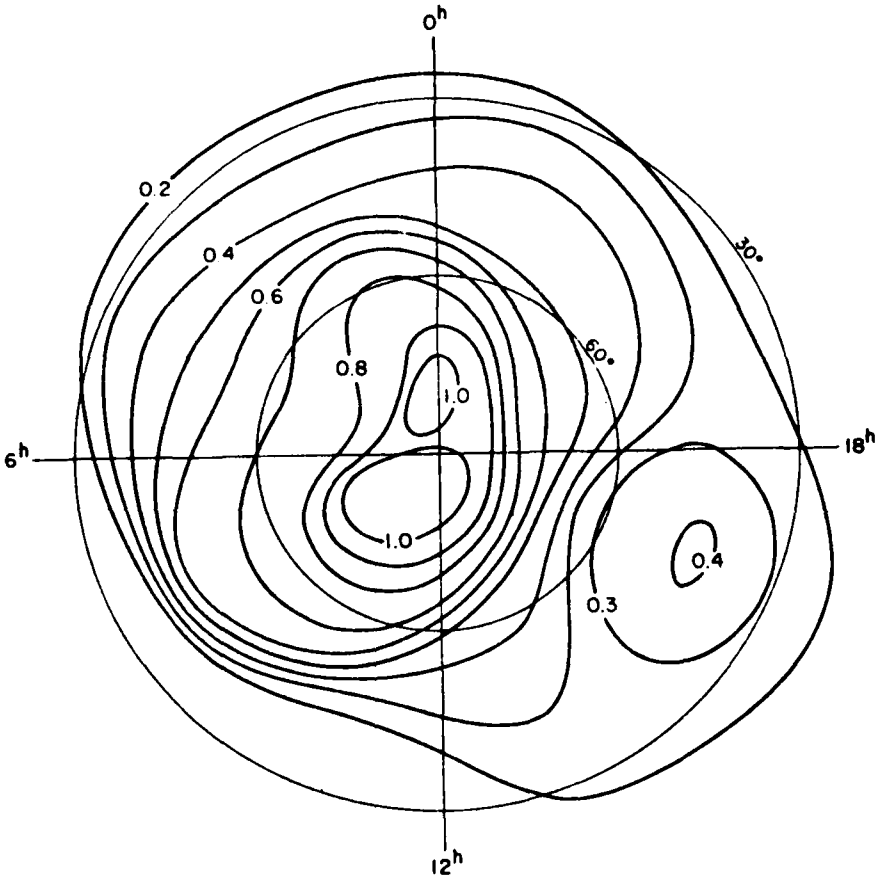
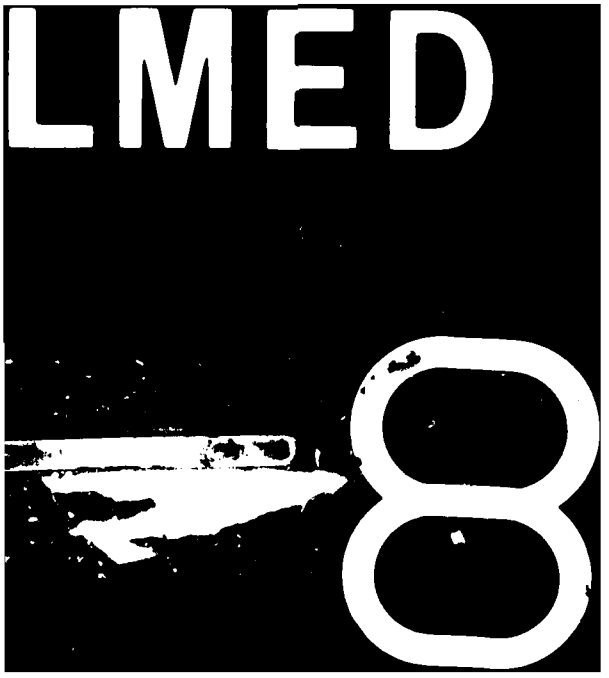


Figure: Isotherms of the mean normalized temperature increase from data with Kp geomagnetic index values in the 3-4 range shown as a function of geomagnetic latitude and local time.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